

Water vapor continuum absorption has been a major source of uncertainty in predicting millimeter-wave attenuation, especially in the window ranges. Moist-air attenuation α at a frequency that falls within a window can be expressed by

$$\alpha = k_s(T)e^2 + k_f(T)e p + k_d(T)p^2 . \quad (\text{A-13})$$

A series of controlled laboratory measurements was performed at 137.8 GHz to determine the k-coefficients. Data $\alpha(T,e,p)$ were taken covering the following range of parameters:

temperature	$T = 8$ to 43 °C
vapor pressure	$e = 0$ to e_1 (RH \leq 95%) and
total pressure	$P = e_1 + p$, where $p = 0$ to 150 kPa.

Experimental data were reduced to a reference temperature $T_0 = 26.85$ °C ($\theta = 1$). The temperature dependence of each k-coefficient ($k_{s,f,d}$) was fitted to a power law $k(T) = k\theta^X$. Moist-air attenuation at $f_x = 137.8$ GHz behaved as follows:

$$k_s = 0.133(4)\theta^{10.3(3)}, \quad k_f = 5.68(5)10^{-3}\theta^{3.0(4)}, \quad k_d = 2(1)10^{-6}\theta^3. \quad (\text{A-14})$$

Values in parentheses give the standard deviation from the mean in terms of final listed digits. The experimental results (A-14) contain foremost contributions from water vapor continuum absorption and were used to "calibrate" MPM by enforcing agreement between experimental and predicted data; further, an f^2 dependence was assumed.

The water vapor continuum is derived from fitting experimental data (A-14) in the case of

$$N_e''(f) = f(b_f p + b_e e) e \theta^3 \quad (\text{A-15a})$$

and based on theoretical data in the case of

$$N_e'(f) = f^2 b_0 e \theta^3 , \quad (\text{A-15b})$$

where

$$\begin{aligned} b_f &= 1.13 \times 10^{-6}, \\ b_e &= 3.57 \times 10^{-5} \theta^{7.5}, \text{ and} \\ b_0 &= 6.47 \times 10^{-6}. \end{aligned}$$

In summary, (A-15) is needed to supplement local line (MPM) contributions, the coefficient b_f is valid only for the selected local line base treated with line shape (A-9), and the strong self-broadening component $b_e e^2$ is nearly unaffected by (A-9). The coefficient b_0 and both exponents in (A-15b) were obtained by fitting dispersion results of line-by-line calculations for the rotational H_2O spectrum above 1 THz.

A.2.3 Suspended Water Droplet Continuum (Haze, Fog, Cloud)

Suspended water droplets (SWD) in haze, fog, or clouds are millimeter wave absorbers. Their size range of radii is below 50 μm , which allows the Rayleigh approximation of Mie scattering theory to be used for calculating refractivity contributions N_w to (A-8) in the form [14] (see p. 73)

$$N_w''(f) = (9/2)w/\epsilon''(1 + \eta^2), \quad (A-16a)$$

$$N_w'(f) = (9/2)w [1/(\epsilon_0 + 2) - \eta/\epsilon''(1 + \eta^2)], \quad (A-16b)$$

and

$$N_w^0 = (3/2)w [1 - 3/(\epsilon_0 + 2)], \quad (A-16c)$$

where $\eta = (2 + \epsilon')/\epsilon''$; ϵ' , ϵ'' are real and imaginary, and ϵ_0 static parts of the permittivity for water. The contribution of (A-16c) is added to equation (A-6).

Values for the dielectric spectra $\underline{\epsilon}(f)$ of water are calculated with a new double-Debye model [15]:

$$\epsilon'(f) = \epsilon_2 + (\epsilon_0 - \epsilon_1)/[1 + (f/f_D)^2] + (\epsilon_1 - \epsilon_2)/[1 + (f/f_S)^2], \quad (A-17a)$$

$$\epsilon''(f) = f(\epsilon_0 - \epsilon_1)/f_D[1 + (f/f_D)^2] + (\epsilon_1 - \epsilon_2)/f_S[1 + (f/f_S)^2], \quad (A-17b)$$

$$\epsilon_0 = 77.66 + 103.3(\theta - 1), \quad (A-17c)$$

where $\epsilon_1 = 5.48$, $\epsilon_2 = 3.51$,

$$f_D = 20.09 - 142(\theta - 1) + 294(\theta - 1)^2 \quad \text{GHz, and}$$

$$f_S = 590 - 1500(\theta - 1) \quad \text{GHz.}$$

Equation (A-17) is valid for frequencies up to 1000 GHz over a temperature range from -10 to +30 °C.

A.2.4 Rain Effects

The refractivity of rain is identified in (A-8) by $N_R = N_R' + jN_R''$. Drop diameters (0.1 - 6 mm) and millimeter wavelengths are comparable, thus causing appreciable interactions due to Mie absorption and scattering. Bypassing elaborate, lengthy Mie calculations which require drop shape and size distributions as well as the complex dielectric properties of water (A-17), rain refractivity spectra are approximated via (see p. 73)

$$N_R''(f) = aR^b \quad (A-18a)$$

$$N_R'(f) = -N_R^0 [x^{2.5} / (1 + x^{2.5})] \quad (A-18b)$$

$$N_R^0 = R(3.68 - 0.012R)/f_R \quad (A-18c)$$

where $f_R = 53 - R(370 - 1.5R)10^{-3}$ GHz and $x = f/f_R$.

Frequency-dependent coefficient a and exponent b were calculated using drop size spectra of Laws and Parsons and a temperature of $T = 0$ °C. A regression fit to individual (a,b)-pairs over the frequency range from 1 to 1000 GHz resulted in the following calculation scheme:

$a = x_1 f^{x_2}$			$b = x_3 f^{x_4}$		
f	x_1	x_2	f	x_3	x_4
GHz			GHz		
1 to 2.9	3.51×10^{-4}	1.03	1 to 8.5	0.851	0.158
2.9 to 54	2.31×10^{-4}	1.42	8.5 to 25	1.41	-0.0779
54 to 180	0.225	-0.301	25 to 164	2.63	-0.272
180 to 1000	18.6	-1.151	164 to 1000	0.616	0.0126

A.3. CONCLUSIONS

The parametric model MPM for atmospheric refractivity

$$\underline{N}(f, P/T/RH, w_A/w, R)$$

was developed for applications in areas such as telecommunications, remote sensing, and radio astronomy. Details of its structure and operation are explained in the extensive COMMENTS part of the code. The memory capacity required for MPM is 355 kbytes.

The format of the numerical print-out is demonstrated by the identical example given in Table A-1 for the \underline{N} version and in Table A-2 for the α/β version. A plotting system at the user's choice (e.g., HALO) can be added to include features such as auto or manual scaling, multiple cases (e.g., nine curves with up to 500 points each), special labels, etc. An example of a graphical presentation for a sea level condition of moist air ($w_A = w = R = 0$) exhibits spectra at various relative humidities ($RH = 0-100\%$) for the \underline{N} version in Figure A-1 and for the identical case as α/β version in Figure A-2.

A.4. ADDITIONAL REFERENCE

Liebe, H. J. and G. G. Gimmestad (1978), Calculation of clear air refractivity, Radio Science 20, no. 2, pp. 245 - 251.

Table A-1.

FREQUENCY PROFILES OF ATMOSPHERIC COMPLEX REFRACTIVITY

INPUT Valid Parameter ranges indicated by []):

CASE	PRES.,P (kPa)	TEMP.,T (C)	REL. HUM.,RH (%)	HAZE MODEL (mg/m3)	SUSP. DROP.,w (g/m3)	RAIN RATE,R (mm/hr)
[1-9]	[0 -110]	[+/-50]	[0-100]	[0-1]	[0-10]	[0-200]
1	101.3	15.0	100.0	: 0.00	1.000	10.0

Minimum Frequency F1 0.000 (GHz)
 Maximum Frequency F2 [1000.]1000.000 (GHz)
 Frequency Step [max 500] dF 100.000 (GHz)

 OUTPUT:

Case Number: 1 (No = 351.18 ppm)

 MOIST AIR (v= 12.81 g/m3)
 DRY AIR + WATER VAPOR + HAZE, FOG CLOUD + RAIN = TOTAL

FREQUENCY (GHz)	N''-IMAGINARY PART (ppm)					N'-REAL PART (ppm)
	DRY AIR	+	WATER VAPOR	+	HAZE, FOG CLOUD	
0.000	+++++		+++++		+++++	+++++
	0.220E-09		-.317E-07		0.278E-08	0.431E-08
100.000	0.168E-02		0.454E-01		0.242E+00	0.317E+00
	-.219E+00		0.321E+00		-.139E+00	-.226E+00
200.000	0.476E-03		0.149E+00		0.288E+00	0.190E+00
	-.170E+00		0.107E+01		-.299E+00	-.266E+00
300.000	0.561E-03		0.174E+00		0.284E+00	0.120E+00
	-.162E+00		0.352E+01		-.391E+00	-.275E+00
400.000	0.807E-03		0.481E+00		0.276E+00	0.869E-01
	-.157E+00		0.619E+01		-.450E+00	-.278E+00
500.000	0.104E-02		0.118E+01		0.268E+00	0.675E-01
	-.162E+00		0.192E+02		-.495E+00	-.279E+00
600.000	0.846E-03		0.225E+01		0.260E+00	0.549E-01
	-.159E+00		-.172E+02		-.532E+00	-.280E+00
700.000	0.977E-03		0.101E+01		0.252E+00	0.461E-01
	-.157E+00		0.687E+01		-.563E+00	-.281E+00
800.000	0.117E-02		0.112E+01		0.242E+00	0.396E-01
	-.161E+00		-.635E+01		-.589E+00	-.281E+00
900.000	0.101E-02		0.795E+00		0.232E+00	0.347E-01
	-.159E+00		0.716E+01		-.611E+00	-.281E+00
1000.000	0.103E-02		0.603E+01		0.223E+00	0.308E-01
	-.159E+00		-.134E+02		-.629E+00	-.282E+00

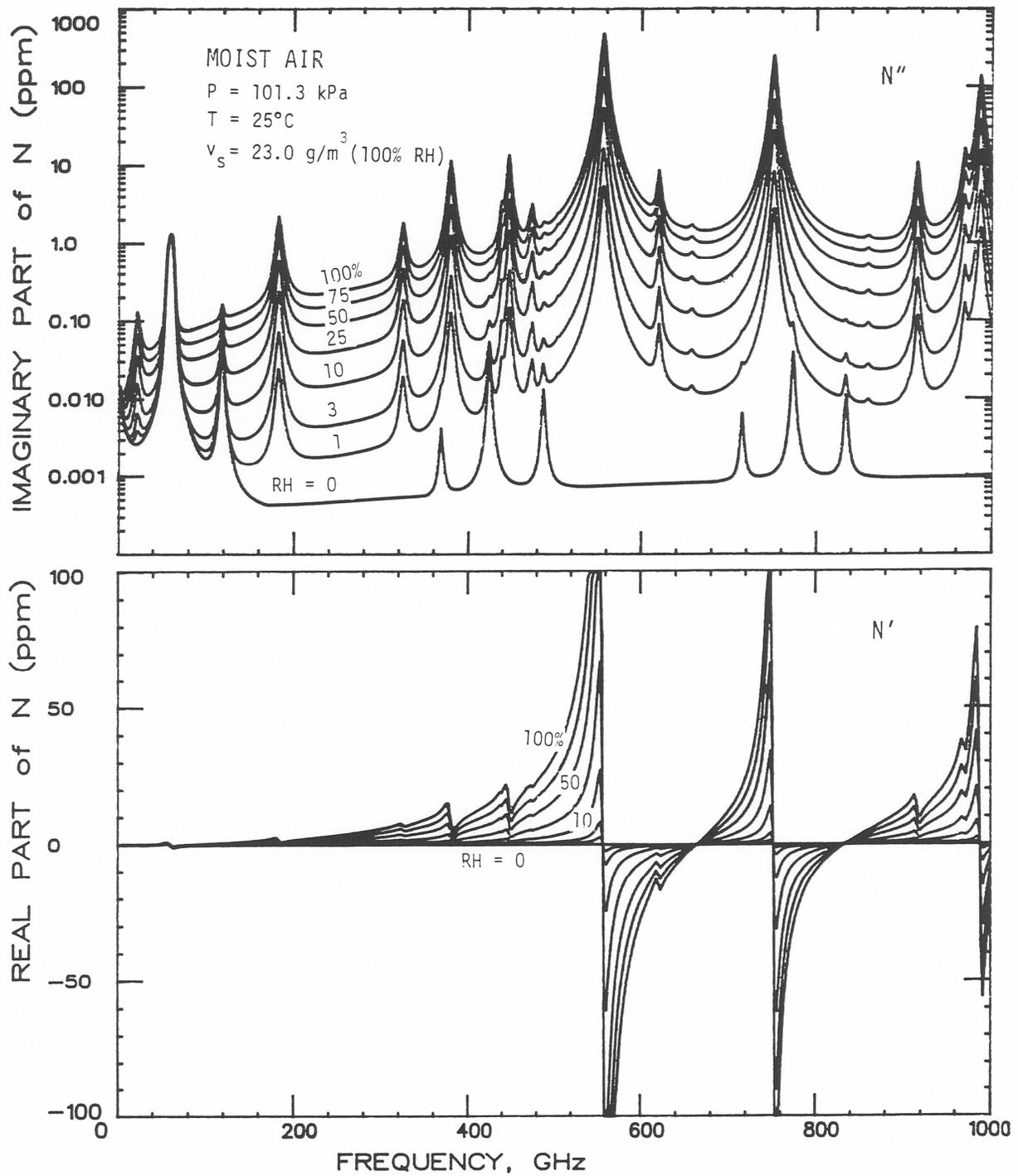


Figure A-1. Moist air refractivity $\underline{N} = N' - jN''$ for sea level condition (P,T) and various relative humidities (RH) over the frequency range from 0 to 1000 GHz.

Table A-2.

FREQUENCY PROFILES OF ATTENUATION AND DELAY RATES

INPUT Valid Parameter ranges indicated by []):

CASE	PRES.,P (kPa)	TEMP.,T (C)	REL. HUM.,RH (%)	HAZE MODEL (mg/m3)	SUSP. DROP.,w (g/m3)	RAIN RATE,R (mm/hr)
[1-9]	[0 -110]	[+/-50]	[0-100]	[0-1]	[0-10]	[0-200]
1	101.3	15.0	100.0	: 0.00	1.000	10.0

Minimum Frequency F1 0.000 (GHz)

Maximum Frequency F2 [1000.]1000.000 (GHz)

Frequency Step [max 500] dF 100.000 (GHz)

OUTPUT:Case Number: 1 (Refractive delay = 1171.5 ps/km)

FREQUENCY (GHz)	MOIST AIR (v= 12.81 g/m3)					= TOTAL
	DRY AIR	WATER + VAPOR	HAZE, FOG + CLOUD	HAZE	RAIN	
0.000	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00
100.000	0.03	0.83	4.41	5.78	11.05	
	-0.73	1.07	-0.46	-0.75	-0.88	
200.000	0.02	5.44	10.50	6.93	22.88	
	-0.57	3.56	-1.00	-0.89	1.11	
300.000	0.03	9.50	15.52	6.57	31.62	
	-0.54	11.75	-1.30	-0.92	8.99	
400.000	0.06	35.02	20.11	6.32	61.51	
	-0.52	20.64	-1.50	-0.93	17.68	
500.000	0.09	107.25	24.43	6.14	137.92	
	-0.54	64.18	-1.65	-0.93	61.06	
600.000	0.09	246.00	28.44	6.00	280.53	
	-0.53	-57.35	-1.77	-0.94	-60.59	
700.000	0.12	128.84	32.07	5.87	166.91	
	-0.52	22.92	-1.88	-0.94	19.58	
800.000	0.17	162.65	35.28	5.77	203.87	
	-0.54	-21.20	-1.96	-0.94	-24.63	
900.000	0.17	130.27	38.08	5.68	174.20	
	-0.53	23.88	-2.04	-0.94	20.37	
1000.000	0.19	1097.36	40.50	5.61	1143.65	
	-0.53	-44.84	-2.10	-0.94	-48.40	

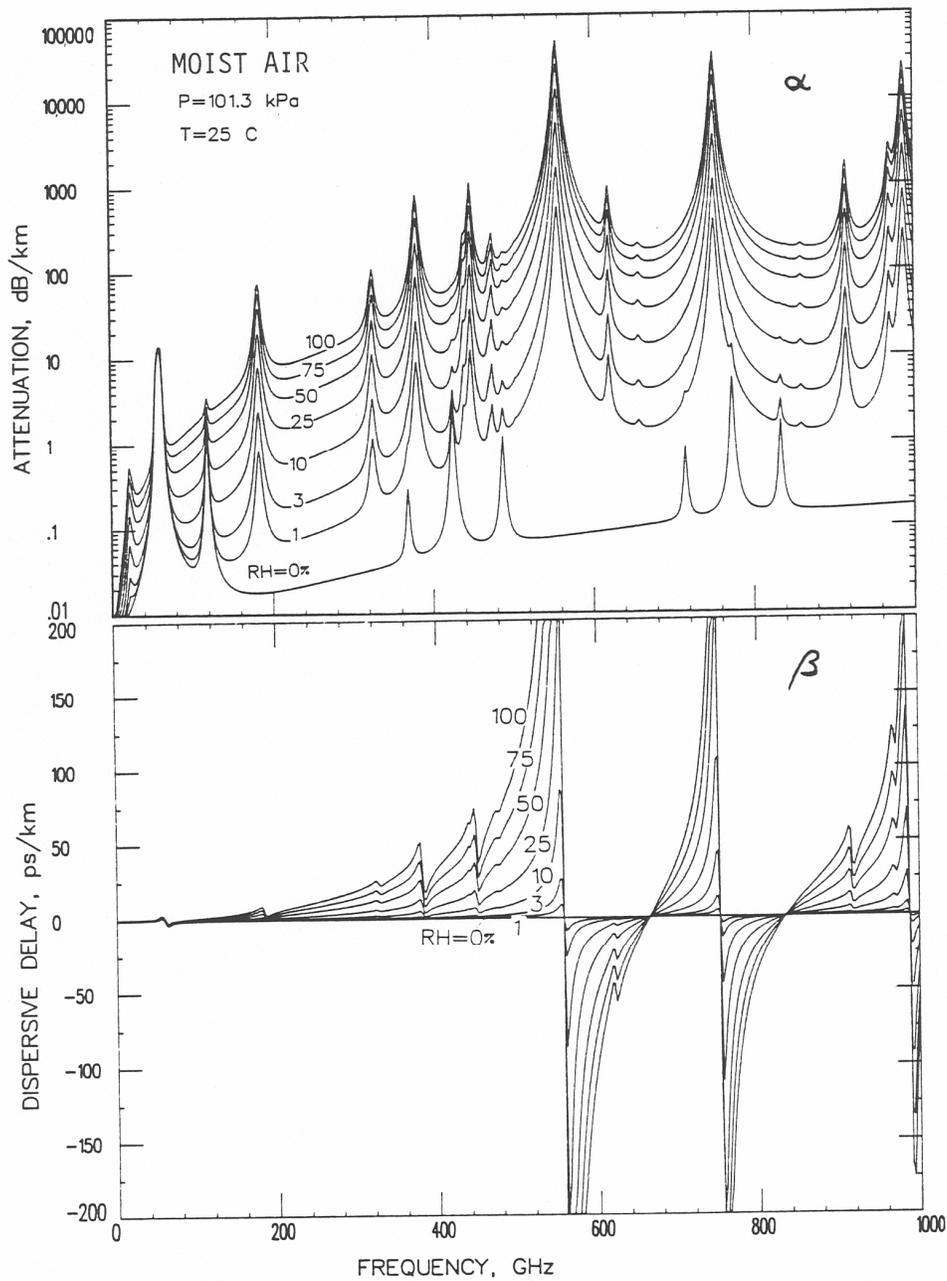


Figure A-2. Moist air attenuation (α) and delay (β) rates for sea level condition (P,T) and various relative humidities (RH) over the frequency range from 1 to 1000 GHz.